

OVERVIEW OF THE STATUS OF RESEARCH REACTORS WORLDWIDE

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ABSTRACT

The IAEA continuously updates the information available on the status of research reactors (RRs) and their spent fuel around the world. This information is gathered in many different ways, including questionnaires, fact-finding missions, expert mission reports, and technical and consultancy meetings. It is then fed into the IAEA's databases. Statistical analyses of these databases provide a useful perspective on the status of the world's RRs and their spent fuel. In this paper an updated review of the information contained in the IAEA's databases is presented. It includes data on the number of RRs operational, shut down, decommissioned, under construction, and planned. Information on the geographical distribution and utilization patterns of the RRs will also be discussed. Particular attention will be paid to the distribution of types of fuel, enrichment and origin of the enriched fuel material.

1. Introduction

For over 50 years, RRs have made valuable contributions to the development of nuclear power, basic science, materials development, radioisotope production for medicine and industry, and education and training.

The worldwide demand for nuclear science education, training, research, technology development, and reactor services has decreased, and no longer requires the large number of RRs currently in operation. Consequently, many facilities are challenged to find users for their services, or to permanently shut down and eventually decommission. Only reactors with special attributes (such as a high neutron flux, a cold source, in-core loops to simulate power reactor conditions) or with commercial customers (such as radioisotope production or silicon doping) are adequately utilized.

Unfortunately, many other RRs are under-utilized. Therefore, many older RRs will be shut down and subsequently undergo decommissioning. New reactors, built in much smaller numbers than in the past, will be either multipurpose reactors or dedicated to specific needs. For example, the new RR under construction in Australia is a multipurpose reactor, while high flux reactor FRMII in Germany will focus on neutron beam research. The two new Maple reactors in Canada are essentially commercial isotope factories designed to produce ^{99}Mo by fission.

Activities in the area of management, interim storage and ultimate disposal of spent nuclear fuel from research and test reactors are dominated at the present time by two important programs. The first is the Reduced Enrichment for Research and Test Reactors (RERTR) program, and the second is the acceptance of spent RR fuel by the country where it was originally enriched.

The world situation of RR spent fuel can be summarized as follows

- 62,027 fuel assemblies in storage;
- 45,108 in industrialize countries;
- 16,919 in developing countries;
- 21,732 HEU assemblies;
- 40,295 LEU assemblies.

Thus, even after 25 years of the reduced enrichment for research and test reactors (RERTR) program, over a third of all stored fuel assemblies are HEU. In addition, there are 24,338 fuel assemblies still in the cores of RRs, and if the large inventory of natural uranium assemblies are discounted, the current cores are roughly equal in numbers of HEU and LEU assemblies.

There are 12,850 spent fuel assemblies of US origin (enriched in the US) still at RRs abroad and most of them are eligible to be returned under the US acceptance program, as long as they are discharged before 13 May 2006.

There are 24,803 assemblies originally enriched in the former Soviet Union, at RRs abroad. Although there is a Tripartite (IAEA, Russian Federation, US) Initiative to repatriate this fuel, so far the first shipment of spent fuel, scheduled to be from Tashkent, Uzbekistan, has yet to take place. In contrast, fresh HEU assemblies have been repatriated from Vinča, Belgrade, and a second shipment from Romania to Novosibirsk was successfully carried out on September 21, 2003. Both shipments were funded by the US with IAEA involvement.

2. General Status of RRs

Most of the information presented in this section is taken from the IAEA's RR Database (RRDB), as of September 2003. Each year the IAEA sends out questionnaires to the owners and operators of RRs requesting an update on information relating to each facility. This information is fed into the RRDB.

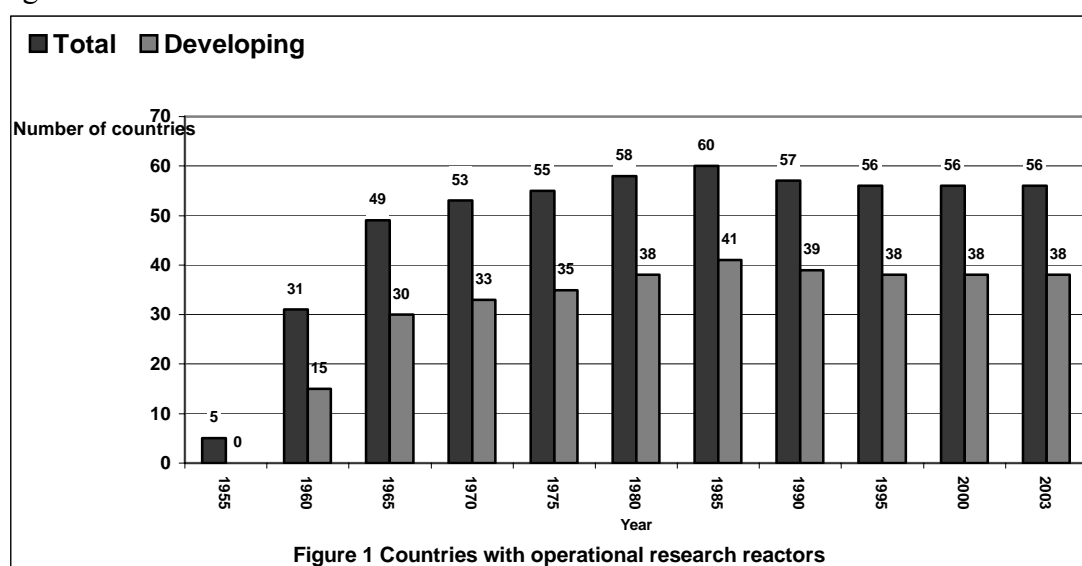
RRDB contains information on 672 RRs that have been built, of which 272 are operational in 56 countries (85 in 40 developing countries), 214 are shut down, and 168 have been decommissioned. Table 1 presents the distribution of RRs, categorized by operational status, between developed and developing countries.

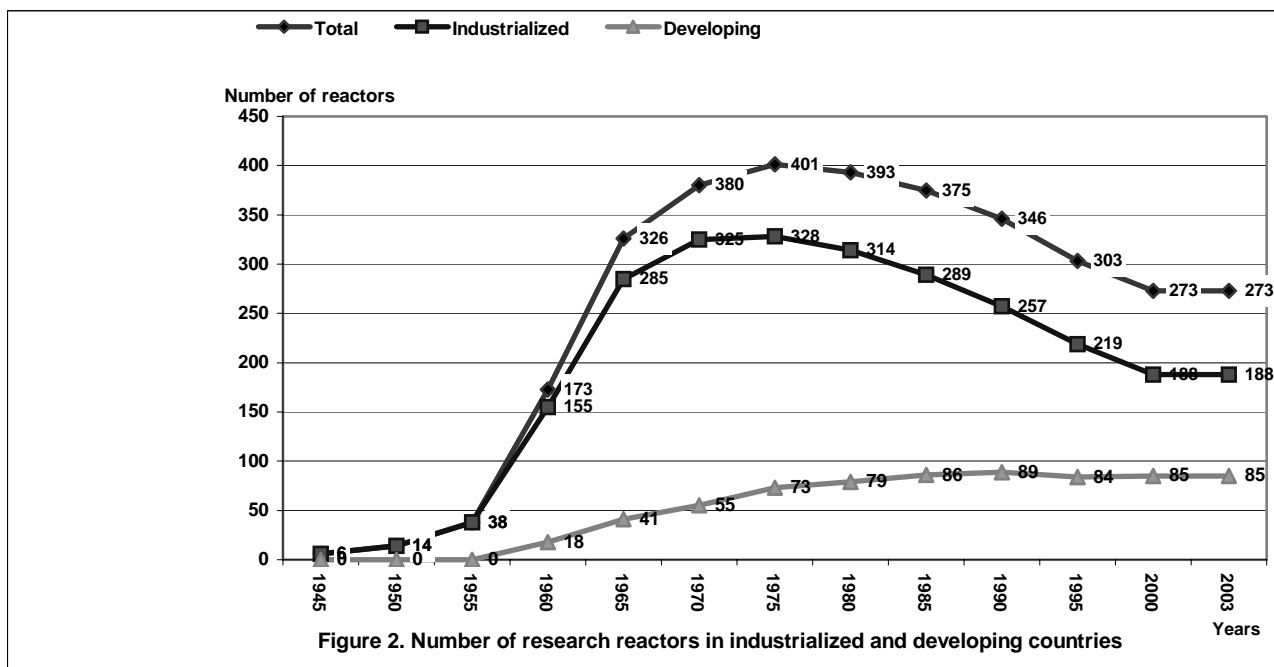
Table 1 Operational Status of Research Reactors

DEVELOPED COUNTRIES	DEVELOPING COUNTRIES
188 IN OPERATION	84 IN OPERATION
187 SHUT DOWN	27 SHUT DOWN
154 DECOMMISSIONED	14 DECOMMISSIONED
3 PLANNED	5 PLANNED
4 UNDER CONSTRUCTION	5 UNDER CONSTRUCTION

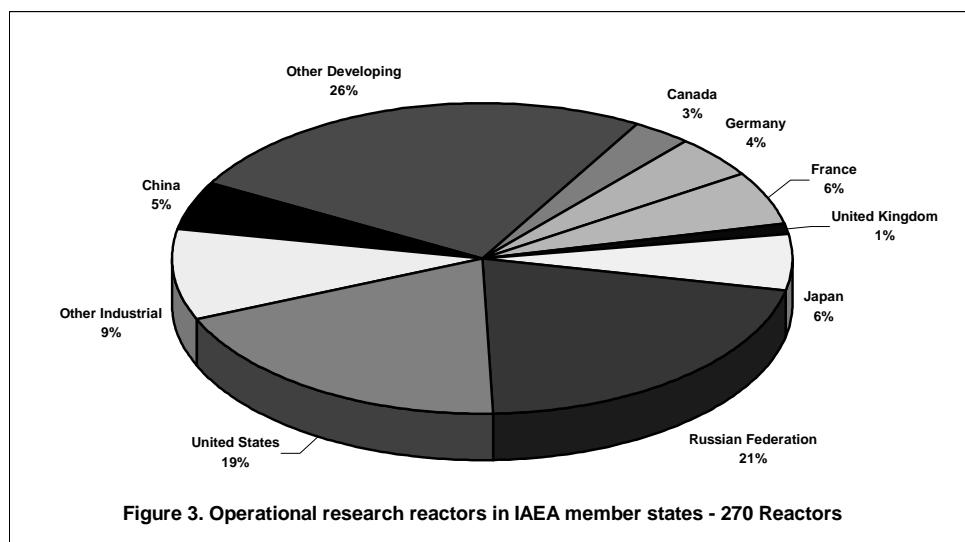
The breakdown of the 672 reactors by operational status reveals that 382 have been shut down, but only 168 have been decommissioned. It is a serious concern that many of the shut down, but not decommissioned reactors still have fuel, both fresh and spent, at the sites. An extended delay between final shutdown and decommissioning will affect both cost and safety at the time of decommissioning, mainly due to the loss of experienced staff (already ageing at the time of shut down) necessary to participate in decommissioning activities. About 70% of all operating RRs are in industrialized countries. Despite the fact that in the most recent decades, many more reactors have been shut down than have been commissioned, 9 new RRs are under construction and 8 more are planned. These new reactors are mostly innovative, multipurpose reactors with high neutron fluxes, which can address many R&D needs.

The distribution of the number of countries with at least one RR, as shown in Fig. 1, peaked at 60 countries in the mid-eighties, in coincidence with the peak at 41 for developing countries. The number of countries with at least one RR remained almost constant for industrialized countries from 1965 and for developing countries from 1985 to the present. 4 industrialized countries and 3 developing countries that once had operational RR no longer have any. Fig. 2 indicates that the number of RRs in industrialized countries peaked in 1975 and has declined since then. The number in developing countries has gradually increased, but changed little since the mid-eighties.

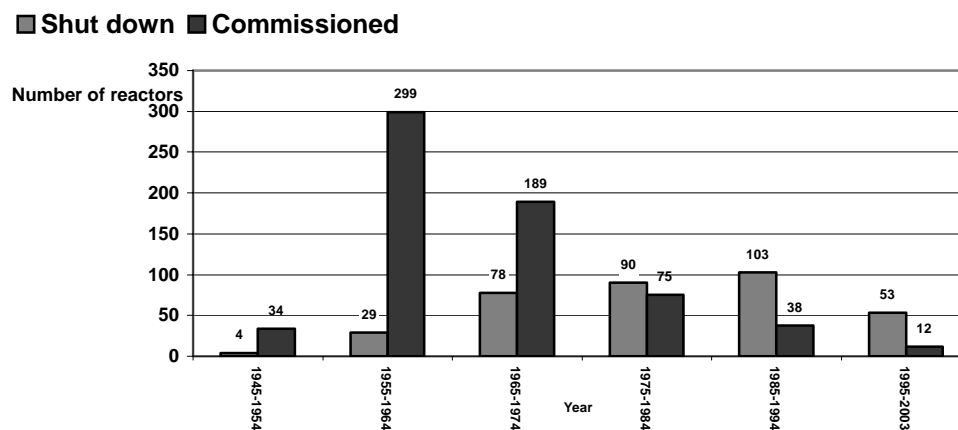




The distribution of RRs among IAEA member states is displayed in Fig. 3. The US and the Russian Federation are the countries with the largest numbers of RRs, with about equal percentages of all operational reactors.

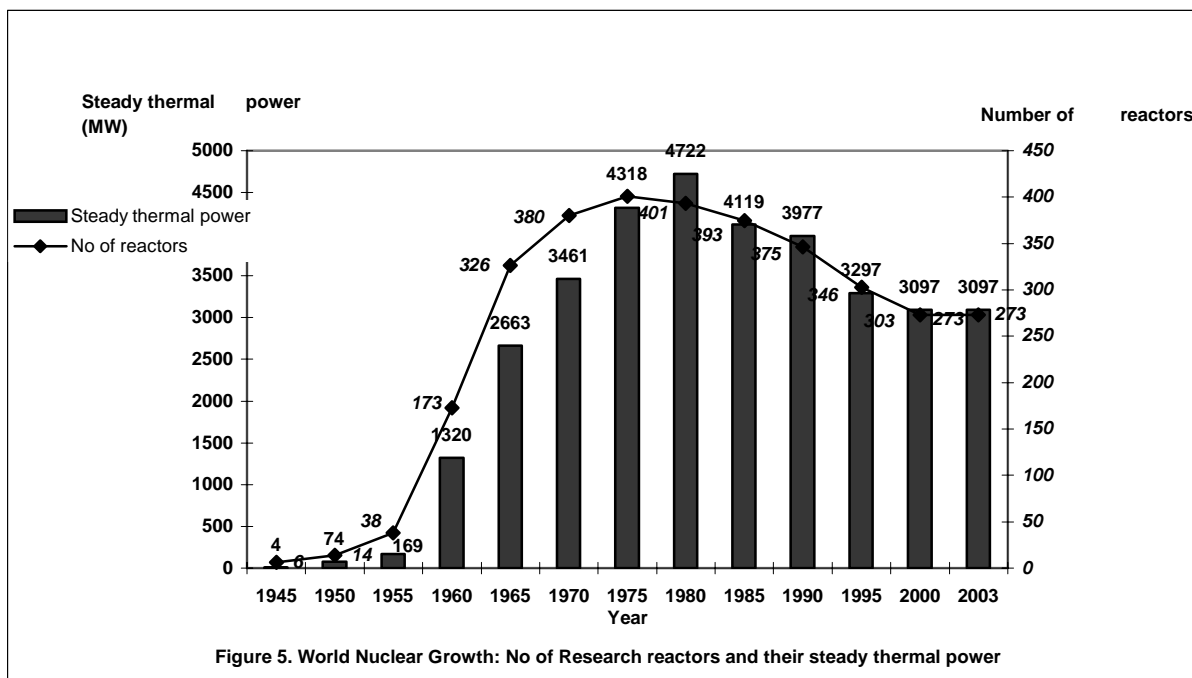


The distribution of the number of RRs commissioned and shut down in Fig. 4 indicates that in the most recent decades, many more reactors have been shut down

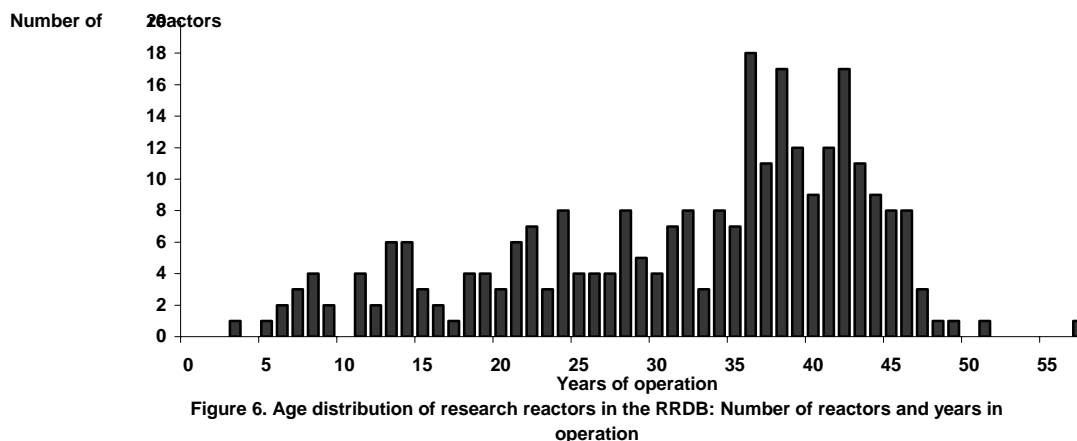


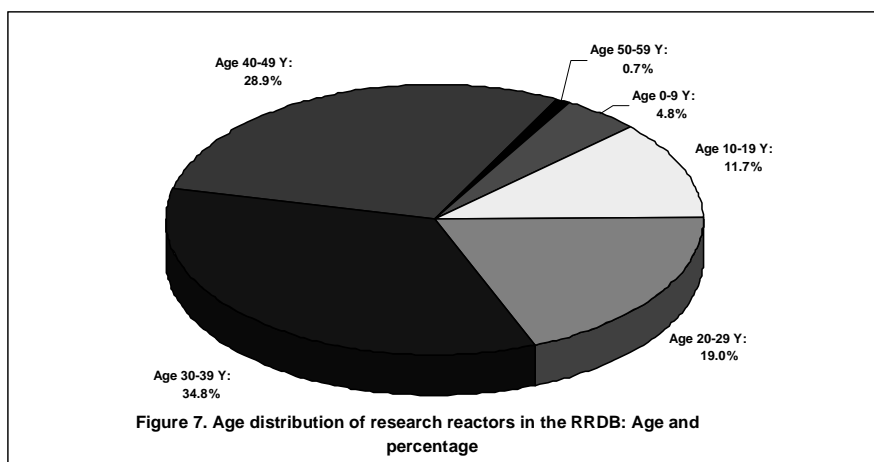
than have been commissioned. Nevertheless, 9 new RRs are under construction and 8 more are planned.

The evolution of the number of RRs and their steady thermal power is presented in Fig. 5. The integral steady thermal power peaked in 1980. The power has been almost at a plateau for the last 8 years, indicating that the significant number of reactors permanently shut down in recent years were mainly in the low power range.

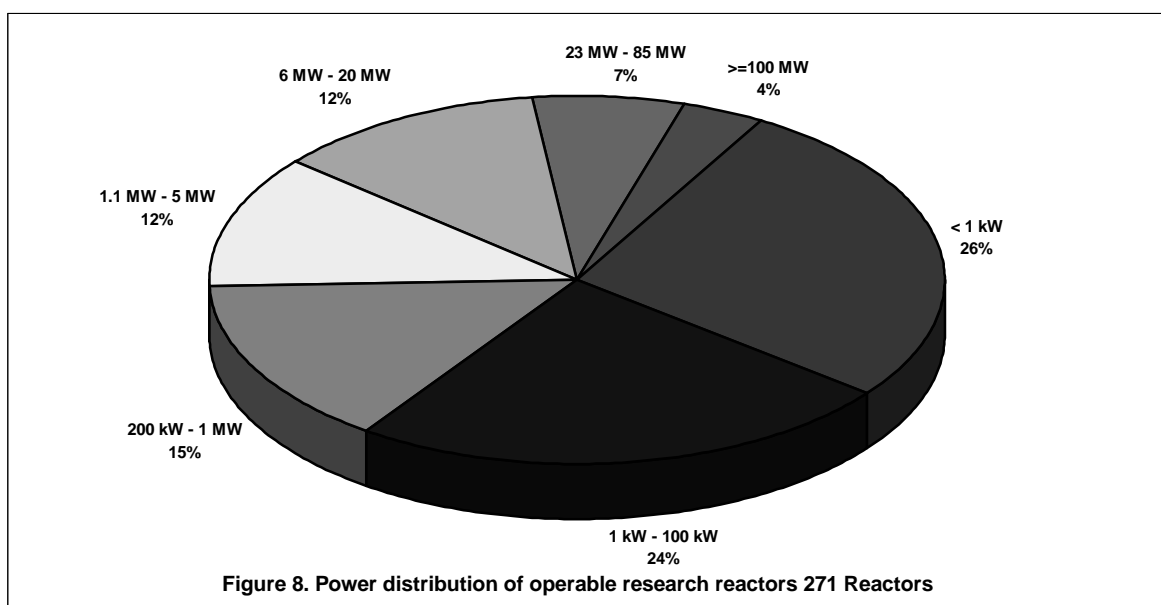


The age distribution of operational RRs peaks in the range of around 40 years (Fig. 6 and 7). Almost 65% of operating reactors are 30 years or older since commissioning. Although a few of these old reactors invoke safety concerns, most have been refurbished, so that the key components meet or even exceed modern safety standards.





The thermal power distribution of operating RRs (Fig. 8) indicates that a large fraction of RRs, 77%, are less than 5 MW, so that even in the worst case accidental scenario, there will not be any significant consequences off site. 50% of operational RRs are less than 100 kW, consequently they operate with a lifetime core and so, no spent fuel problems will arise until these reactors are shut down permanently.



3. Spent Fuel Management

Most of the information presented in this section is taken from the IAEA's RR Spent Fuel Data Base (RRSFDB), as of September 2003. RRSFDB contains 210 entries. Of these RRs, 44 are permanently shut down, 14 are temporarily shut down for refurbishment, 4 are planning shut down, 3 have unverified information on status and the remaining 145 are operational. Spent fuel is usually an ongoing liability after a reactor is shut down and the IAEA would like to include details of spent fuel, if it has not been reprocessed, from all of the known 214 shut-down reactors not yet decommissioned reported in RRDB. In addition, there is a large discrepancy between the 272 operational reactors in RRDB and the 145 reactors that have so far responded to the questionnaires for RRSFDB. Fortunately, most research and test reactors with substantial turnover of fuel and, hence, significant inventories of spent fuel, are included in RRSFDB. Nevertheless, it is essential for the IAEA to get a clear and accurate picture of the problems faced by RR operators and their concerns about

management, storage and ultimate disposal of spent fuel, in order to be able to address them and to exert pressure internationally for the implementation of spent fuel take-back programmes by supplier countries and to begin a dialogue about possible regional repositories as an ultimate solution for countries with no nuclear power programme.

The remainder of this section deals with numbers of fuel assemblies, their types, enrichment, origin of enrichment and geographical distribution among the industrialised and developed countries of the world.

Accumulated Spent Fuel

Most RR fuels are shipped in assembly form. For this reason, in RRSFDB spent fuel numbers are recorded in assemblies, where a fuel assembly is defined as “the smallest fuel unit that can be moved during normal reactor operation or storage”. Even so, questions regarding numbers of fuel assemblies obviously caused confusion to respondents to the questionnaires. Consequently, the data received has been reviewed and corrected by a panel of experts who know the details of the various fuel assembly designs. At any particular facility, several different spent fuel types or spent fuels of different enrichments are usually stored. For example, the store may contain one or more types of HEU from prior to core conversion and one or more types of LEU following conversion.

Several facilities report more than three types of spent fuel and for this reason the records in RRSFDB store up to ten fuel types per facility. Strictly speaking, fuels enriched to $\geq 20\%$ ^{235}U are classified as HEU. Since many facilities with LEU cite a nominal enrichment of 20%, we have modified the definition of LEU to be $\leq 20\%$ ^{235}U for the purposes of RRSFDB. Since any fuel with exactly 20% enrichment before irradiation will have $<20\%$ enrichment after significant burnup, this does not violate the accepted definition.

The distribution of fuel types among the reactors in the RRSFDB is shown in Table 2. Although the majority are of MTR, TRIGA or standard Russian types, a significant percentage (28%) are classified as other types which underlines the fact that many experimental and exotic fuels exist at RRs around the world, posing problems for their continued storage, transportation and ultimate disposal.

Table 2: Distribution of Reactors by Fuel Type

FUEL TYPE	REACTORS USING FUEL TYPE	
	NUMBER	PERCENTAGE
MTR	67	32
TRIGA	40	19
RUSSIAN	43	21
OTHER	58	28

The regional distribution of spent fuel, with a distinction made between developing and industrialised countries, is shown in Fig. 9. As might be expected, the majority of spent fuel assemblies are stored in the industrialised countries. The origins of the enrichments of the RRSFDB spent fuel inventory are broken down into fuel of

US, Russian, and other origin in Fig. 10. In this case, others include China, France, UK, South Africa, natural uranium fuels and those cases where the origin of enrichment was not known or simply left blank on the questionnaire. As expected, the US supplied all of the enriched fuel in North America and most of that in Asia-Pacific, while Russia (or the former Soviet Union) supplied most of the enriched fuel in Eastern Europe.

The regional breakdown of US-origin and Russian-origin fuel, classified as HEU or LEU, is shown in Fig. 11. This involves totals of 5341 HEU and 7509 LEU assemblies of US-origin and 8579 HEU and 16,224 LEU assemblies of Russian-origin. Of interest in this Figure is the fact that HEU outweighs LEU in North America, whereas the reverse is true in Western Europe. To some extent this is because more RRs in Western Europe have undergone core conversion than is the case in North America. It is worth noting that a significant fraction of Russian-origin HEU was originally enriched to only 36%, while most US-origin HEU was originally enriched to $\geq 90\%$. Also, the inventory of spent fuel assemblies of Russian origin contains many thousands of small, spent fuel slugs and EK-10 elements, which considerably inflates the numbers of spent fuel assemblies of Russian origin compared with those of U.S. origin. In fact, the amounts of ^{235}U involved are very much bigger in the US inventories at foreign RRs compared with the Russian equivalents. This is particularly true of the respective amounts of HEU.

Overall, there are 62,027 spent fuel assemblies stored in the facilities that have responded to the RRSFDB questionnaires to date and another 24,338 assemblies in the standard cores. Of these 62,027, 45,108 are in industrialized countries and 16,919 are in developing countries, while 21,732 are HEU and 40,295 are LEU.

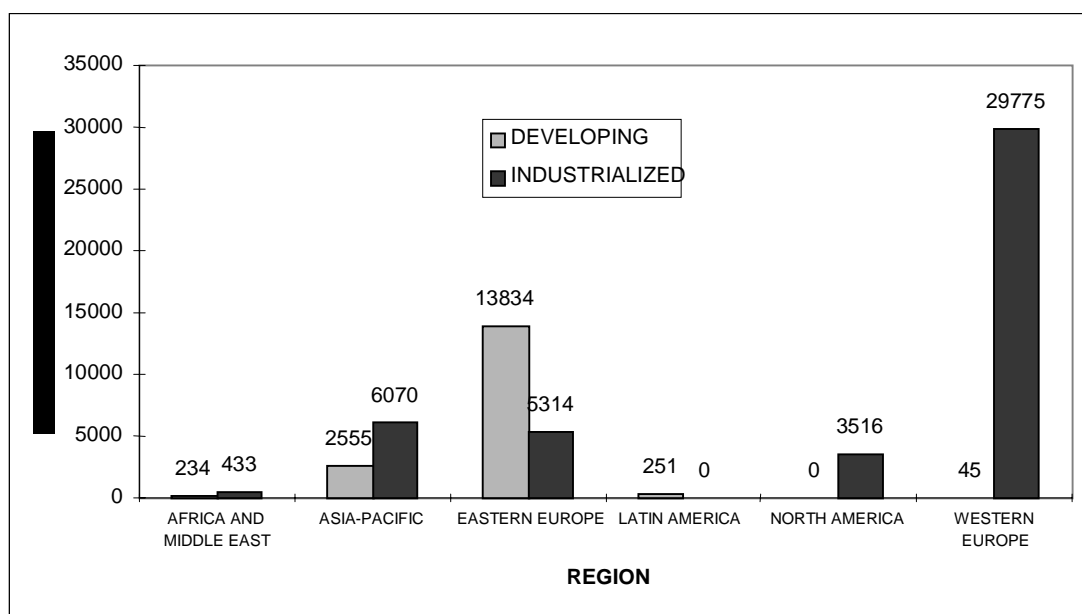


Figure 9: Distribution of Spent Fuel Between Developing and Industrialized Countries.

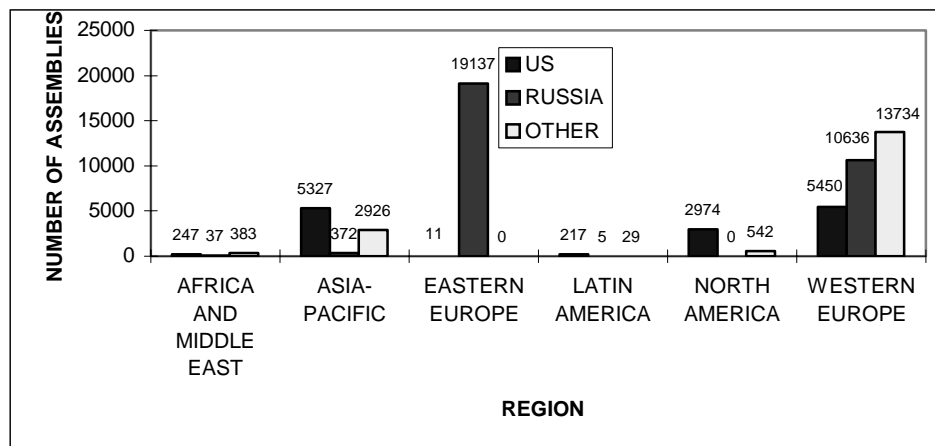


Figure 10: Geographical Distribution of Spent Fuel by Supplier Country.

The numbers of US-origin and Russian-origin HEU and LEU spent fuel assemblies at foreign RRs, which might be involved in take-back programs, are compared in Figure 12. These projections assume no returns in the interim, which will not be correct in the case of US-origin fuel.

At present 12,850 spent fuel assemblies of US-origin are located at foreign RRs, while the equivalent number of Russian-origin is 24,803.

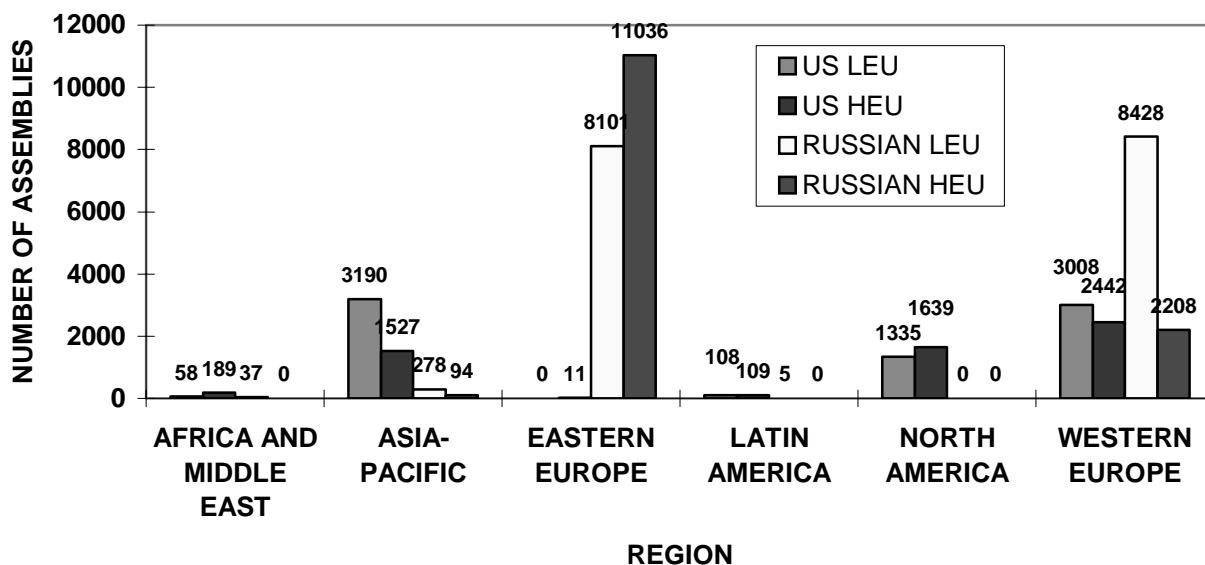


Fig 11 Geographical Distribution of US and Russian Origin Fuel by Enrichment

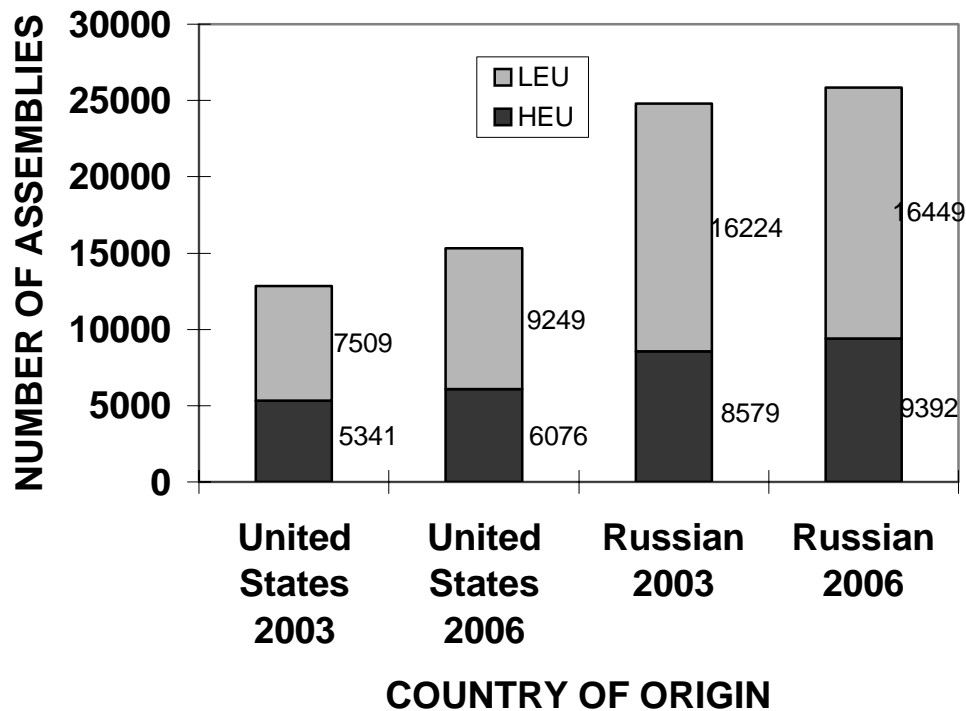


Figure 12: Present and Projected Spent Fuel at Foreign Research Reactors

4. Regional Spent Fuel Storage Facilities

In his Statement to the Forty-seventh Regular Session of the IAEA General Conference 2003, the Director General of IAEA, Dr. Mohamed ElBaradei, stated:

“Our consideration should also include the merits of multinational approaches to the management and disposal of spent fuel and radioactive waste. Not all countries have the appropriate conditions for geologic disposal - and, for many countries with small nuclear programmes for electricity generation or for research, the financial and human resource investments required for research, construction and operation of a geologic disposal facility are daunting. Considerable economic, safety, security and non-proliferation advantages may therefore accrue from international co-operation on the construction and operation of international waste repositories. In my view, the merits and feasibility of these and other approaches to the design and management of the nuclear fuel cycle should be given in-depth consideration. The convening of an Agency group of experts could be a useful first step”.

Several countries with a small nuclear power programmes or one or more RRs face the serious problem of extended interim storage and disposal of their spent nuclear fuel. The expensive construction of away-from-reactor extended interim storage facilities and/or geological repositories for the relatively small amounts of spent fuel accumulated in such countries is obviously not practicable and, therefore, access to a regional or international interim storage facility and/or repository for their fuel would be an ideal solution. It is also clear that acceptance programmes of foreign RR fuel, if and when they are implemented, will not continue indefinitely. Thus the time is ripe for serious discussion of such regional facilities and to begin planning for

the day when neither acceptance programmes nor the reprocessing options might be available for RRs and reprocessing of power reactor spent fuel declines.

It is interesting to note that *effectively* RSFSFs exist in several countries, for example, RR fuel from all over the world, but originally enriched in the U.S., is at present stored in wet interim storage pools at the Receiving Basin for Offsite Fuel (RBOF) and the L-basin at DOE's Savannah River Site, pending final disposition. Nonproliferation is the driving force for the operation of these facilities. In addition, the holding pools at reprocessing plants like Mayak in Russia and La Hague in France also effectively act as RSFSFs.

5. Conclusions

A sound statistical analysis of the information contained in the IAEA's databases is a useful resource to assess the overall status of RRs and their spent fuel around the world, to understand the potential problems and to identify trends in operation, utilization and nuclear fuel cycle issues.

Issues such as utilization, cost effectiveness, stakeholder's satisfaction, safety and the level of funding constitute, at present, the main set of concerns of RR operators. They should be addressed with a holistic approach through a complete strategic plan, developed using the modern strategic planning tools.

In recent years the problems of spent fuel from RRs have received increasing attention as concerns about ageing fuel storage facilities, their life extension and the ultimate disposal of spent fuel loom larger. Regional and international approaches are likely to be considered increasingly, especially by those countries with no nuclear power programmes, only one or more RRs and consequently very little spent fuel production.

6. Reference

[1] Dodd, B.; Dolan, T. J.; Laraia, M.; Ritchie, I., Perspectives on Research Reactor Utilization, *Physica B* 311 (2002) pp.50-55